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Research Paper

Hybrid finite-discrete element modelling of dynamic fracture and resultant fragment casting and muck-piling by rock blast

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ABSTRACT

A state-of-the-art review is conducted to highlight the fracture mechanism in rock blast and advantages and limitations of various methods in modelling it. A hybrid finite-discrete element method (FEM-DEM) is implemented to simulate rock fracture and resultant fragment muck-piling in various blasting scenarios. The modelled crushed, cracked and long radial crack zones are compared with those in literatures to calibrate the hybrid FEM-DEM. Moreover, the hybrid modelling reproduces the rock fragmentation process during blasting. It is concluded that the hybrid FEM-DEM is superior to continuous and discontinuous methods in terms of modelling dynamic fracture of rock under blast-induced impact load.

1. Introduction

Blasting has been widely employed in the mining industry for many centuries and it remains a popular method of rock fragmentation, hard rock tunnelling and structure demolition in modern mining and civil engineerings. In mining engineering, the rock fragmentation by blasting is the first stage of the comminution process in mines and is the activity that may have the most leverage in the efficiency of a mining operation, as the output from a blast impacts every downstream operation. An improved fragmentation associated with blasting can result in efficient rock breakage, reduced costs for both secondary fragmentation and transportation of the blasted rock, effective destressing of rockburst prone area, improved environmental aspects, and reductions in energy consumption during crushing and grinding of the ore, as well as improved metal recovery. In civil engineering, controlling both fragmentation and the degree of blast induced damage in the hard rock tunnelling and structure demolition are important aspects of the project design process. Poor blasting practices are typified by excessive damage and over-break, oversize fragmentation, restricted access, increased local reinforcement requirements and increased project cycle times and costs. Therefore, it is essential to study the rock fragmentation by blasting with an aim of whether inducing considerable fracture and fragmentation of rock or preventing failure of rock engineering structure under blast loads.

2. Review of previous studies on rock fragmentation process by blasting

Considerable efforts were made in the last four decades to understand the rock fracturing mechanism in rock blasting and many studies concluded that the current situation in rock blasting is far from the theoretical optimum fragmentation [1–5]. The potential for improving blasting in mining, civil, petroleum and defence engineerings is huge and the economic potential is enormous. Blast fragmentation modelling is an important step to achieve the optimum fragmentation, which allows the estimation of blast fragmentation distributions for a number of different rock masses, blast geometries and explosive parameters. In the past, empirical models were put forward by some researchers [6–8]. These models were mainly developed based on the attributes observed after rock blasting, especially the size distribution of rock fragments. In 1930s, Rossin and Rammler [9] proposed the Rosin-Rammler equation to characterize the particle-size distribution of material. Later, Kuznetsov [7] developed a semi-empirical equation for estimating the size distribution of rock fragments. The Kuz-Ram model [8,10] is probably the most widely used approach and the

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modified Kuz-Ram model was used by Gheibie et al. [11] at Sungun Mine to predict the fines produced during blasting. The other important empirical models include the JKMRC blast fragmentation models [3], e.g. the Two-Component Model [12] and the Crushed Zone Model [13], and the Swebrec functions [14]. Since the empirical models require only a few of input parameters for engineering applications, they can be easily applied in routine blast design layout spreadsheets [8,10]. However, limited input parameters may lead to inaccurate prediction. In addition, in regards to the practice, several blastings must be tested frequently in advance, which makes the implementation of the empirical models expensive and time consuming. Moreover, the empirical model may not be able to satisfy the requirements of the modern rock blasting engineering since rock fracture and fragmentation progresses are ignored in the empirical model. As a matter of fact, the rock blasting is an extremely complex process and, generally, involves explosive detonation, gas expansion, stress wave propagation, rock fracturing and resultant rock fragment throwing and muck-piling. The lack of understanding of the complex process of the rock blasting has limited engineers to optimize rock blast design. Thus, this paper is intended to study the rock blasting process from the mechanics point of view.

2.1. Review of dynamic rock fracture mechanism during rock blasting

Many researchers have conducted experimental and theoretical studies of the rock blasting processes in order to understand the rock fragmentation mechanism and then improve rock blasting efficiency. Latham et al. [15] charted the researches on the understanding of rock blasting processes drawing upon the work of researchers worldwide in the 1980's and 1990's. More recently, Saharan et al. [16] presented a detailed state-of-the-art review on the study of the dynamic rock fracture initiation and propagation due to explosive energy. In their review, explosive energy dissipation in crushing and fracturing was examined, the various means to enhance the explosive energy utilization for dynamic rock fracturing were reviewed, and the need for a better understanding of the dynamic fracturing process was particularly highlighted. According to these reviews, the different rock breaking mechanisms in rock blasting, such as tensile reflected waves, compressive stress wave, gas pressure, flexural rupture and nuclide stress flow, were propounded by various researchers in literatures but there is no agreement between the various researchers. However, it is generally accepted that the tensile reflected wave, and the coalescence of stress wave and gas pressure are the mainly reasons contributing to the rock fracture and fragmentation in rock blasting. Correspondingly, they are reviewed here in detail.

At one stage, the tensile reflected waves were considered as the predominant means of rock fracture and fragmentation in rock blasting, which is true especially for the situations when there are one or more free surfaces. Hino [17] proposed that the major rock failure was caused by the reflection in tension of the primary shock wave. According to his theory, as depicted in Fig. 1(a–c) and (e), while the detonation of an explosive charge produces a crushed zone, a shockwave with high peak pressure but short of duration propagates outwards as a compressive wave. As the shock wave attenuates, it does not produce more breakage besides the cracks in the crushed zone. After it reaches free surface, the compressive wave reflects as a tensile wave. Since the tensile strength of rock is smaller than its compressive strength, the rock fracture occurs at the areas with the intensive tensile wave, i.e. the free surface area and its vicinities. If the compressive wave remains after the first shock wave reaches free surfaces and is reflected as tensile wave, the processes are repeated at newly produced free surface [17]. Theoretically, the processes will also occur at joints which naturally exist in the rock. As well known, in mining and civil engineering blasting practices, a free surface is normally made before blasting and the fragmentation is produced mainly from the free surface areas. Thus, this model seems reasonable. Nevertheless, if there is no any free surface, the tensile reflected wave may not play such a significant role. Bhandari [18] conducted the single blasthole tests in both cement-mortar and granite and concluded that in large fragments (e.g. boulders) the stress wave reflection and scabbing actions were weak.

The gas pressure was once considered playing a significant role in rock blast [19]. Dally et al. [20] focused their study on the effect of the gas pressure from the combustion products of an explosive charge on the rock fracture process. Two plane models with a centrally located circular charge were constructed by them. In one of these two models, the charge was vented, so that the cracks produced around borehole could be caused only by the stress wave. In the other model, the charge was contained with a special sealing device in order to observe the action of the gas pressure in extending the cracks. They concluded that the containment of the charge (i.e. the containment of gas) in the hole caused more extensive fracturing. Besides Hino [17] and Dally et al. [20], there were other researchers concentrating on just limited aspects of the blasting process, such as either the initial explosive strain pulse [21–24] or the gas pressure [25–28], which were thought as the main cause of the rock fracture and fragmentation, while other factors were neglected [29]. However, more sophisticated theory should consider all the aspects controlling the rock fracture and fragmentation process during the rock blasting.

The coalescence of the compressive stress wave and the gas pressure are widely accepted to result in the rock fracture and fragmentation in rock blasting in the literature [30]. Kisslinger [6] divided the region around the detonation into three zones: a strong shock zone (which was mainly produced by the shock wave), a transitional and nonlinear zone (in which both the shock wave and the gas pressure played a significant role), and the elastic region (which was produced under the gas pressure). Generally speaking, the three zones are produced by the forces exerted by the gas pressure and the stress wave simultaneously and it is almost impossible to separate the two principal blast forces. However, Kutter and Fairhurst [29] studied the roles of the stress wave and the gas pressure respectively in producing the rock fragmentation by underground blasts. In their studies, a pulse generated by an underwater spark discharge was used to simulate the explosive wave, and the pressurized oil was used to simulate expanding combustion i.e. the gas pressure. Since this theory has been widely accepted, we introduced it here in detail in order to provide a comparison with the numerical results to be presented later in this paper.

Fig. 1(a)–(d) depicted the blast-induced rock fracture process proposed by Kutter and Fairhurst [29]. As shown in Fig. 1(a), the strong-shock zone lies in the region immediately around the borehole. When the chemical charge is detonated, a high temperature and density gas coupled with an extremely high pressure pulse, i.e. explosive wave, is generated. The high pressure pulse transmits in the rock adjacent to the borehole producing a dilatational wave, which propagates away from the charge at the sonic velocity in the rock [20]. The corresponding high pressure, which may exceed several-fold of the compressive strength of the rock, is exerted on the rock immediately around the borehole resulting in the vicinity around the borehole being intensively crushed and shattered. The first zone, i.e. the crush zone, is formed as shown in Fig. 1(a). In the crushed zone, the elastic rigidity of the rock is completely insignificant [29] and the crush is caused by both the compressive stress and the tangential stress but the compressive stress plays a more significant role. Moreover, the crushed zone is characterized by the shattered, smallest and relatively uniform particle size. The second zone, i.e. the transitional and non-linear zone or the cracked zone shown in Fig. 1(b), is characterized by